Computer-Aided Engineering for Tool Design in Manufacturing Engineering Curriculum

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Abstract

At Cal Poly – San Luis Obispo, a variety of tool design issues are covered in a junior-level manufacturing engineering course called Tool Engineering. In the course, designing fixtures – for any process – is a major component of the content. The process of designing a fixture is similar to the method a mechanical engineer would use to design a new product. The course is therefore an excellent opportunity to teach design principles to manufacturing engineers. This project involves an attempt to introduce computer-aided methods, including the finite element method (FEM), for analysis of tool design into the Tool Engineering course. The approach is to cover in 2-3 lectures the basic principles of FEM without getting into computational algorithms. A healthy skepticism for software results and the need for validation tests are encouraged and explained. A series of labs (using FEM software) has also been developed to analyze and optimize fixture designs, mold and die designs, and product "design for fixturing."

I. Introduction

Tool design in manufacturing industry has long been an "art-form" requiring years of experience and familiarity with processes and available tooling. Manufacturing engineering programs have struggled with how to teach the subject, resolving mostly to include it in courses on individual processes (e.g., design of cutting tools in a material removal class, design of molds in a casting class, etc.). This approach leaves manufacturing engineers without an understanding of the overall methodology of design, especially as compared to their counterparts getting mechanical engineering degrees. This knowledge gap is critical as manufacturing engineers join mechanical engineers (and other engineers) on concurrent design teams where they must work with and contribute to design efforts. Furthermore, in today's design world computer-aided engineering (CAE) tools, especially those using the finite element method (FEM), play an important role for product designers and represent another area to which manufacturing engineers may not be exposed.

Like other design tools, FEM can be applied to process tooling design. It's capability for simulating static and dynamic response of the modeled object makes it a perfect tool for aiding the design of fixtures and tooling for manufacturing processes. FEM is important for tool design because it helps to analyze rigidity and because of the influence of rigidity on the overall success of the design. Particularly with part fixtures, rigidity affects dimensional control due to resistance to static deflection and it affects surface finish and safety due to resistance to dynamic vibrations. An example of the use of FEM for static and dynamic fixture analysis is presented by Landgraf[1] for holding a cast component for Porsche automobiles. Similar analyses can be performed on cutting tools and tool holders, as illustrated in a paper by Mason[2]. Furthermore, other tooling solutions, such as molds for casting and injection molding and dies for stamping and forming are now regularly being analyzed using FEM, as discussed in two recent articles[3,4]. Without some experience with this tool, manufacturing engineering students are at a disadvantage for solving problems on the job and in competing with other mechanical engineers for similar manufacturing-related jobs.

The junior-level course Tool Engineering (3 hours lecture and one 3-hour lab per week) at Cal Poly is designed primarily for manufacturing engineering majors as an intermediate course on workholding, jigs and fixtures, molds and dies, advanced tooling concepts such as modular and flexible fixtures, and tooling for robotic assembly. Rather than treating each process as a separate entity for learning the tooling technology, the course presents an overall strategy for design that considers function, quality, productivity, cost, and safety. The same strategy is applied to each area for designing a tooling solution. Students must follow a traditional approach to design in which they define the problem, identify constraints and requirements, develop alternative solutions, analyze the alternatives, and select a design. They are periodically required to orally defend their designs in an informal “design review” in front of the class. For the analysis step, the course covers cost estimation, locating and clamping principles, and productivity and safety considerations. In the past, the course has stressed rigidity as a key to meeting functional and quality (even safety) requirements, going so far as to list the three most important factors for good tool design as rigidity, rigidity, and rigidity. However, the course inadequately covered mechanical analysis of the design. Even though students must have taken pre-requisite courses in engineering statics, materials engineering, and strength of materials, no rigorous analysis of the deflections or dynamic response of the tool designs was expected. This lack of analysis was generally due to the geometric complexity of the designs and the corresponding difficulty with mathematical modeling of tool behavior.

The finite element method makes these complex analyses possible, and software for FEM analyses is becoming more easily available and pc-compatible. The method’s main purpose is to apply basic mechanical equilibrium equations to complex model geometries by integrating contributions from many small, simple element shapes. The approach can thus approximate mechanical and thermal responses of complex objects through computer simulation. The software itself can be very complex and prone to misuse[5,6], but many schools have introduced undergraduate courses that cover the method. MacLeod[7], Owen[8], and Pomeranz[9] discuss general strategy issues for teaching FEM to undergraduates. In an undergraduate finite element analysis (FEA) course at Purdue[10], the goals are “to develop proper modeling techniques and interpretation of FEA results, with emphasis on the need for verification of the FEA results.” Middleton[11] describes the introduction of FEM in an undergraduate mechanical engineering course on mechanical design. In the course, only simple structural analyses are solved with FEM so students get a feel for the approach. The intent is to give the students some experience and confidence so they can apply the method to a more complex structure in a capstone project course. Several other schools[12-19] have also introduced FEM into undergraduate civil and mechanical engineering (and engineering technology) courses and provided a discussion of their experiences. No evidence has been found, however, of the use of FEA in a manufacturing engineering curriculum.

The goal for this project is to introduce the finite element method into the Tool Engineering course for use in tool design. Specific objectives include:

- Make students aware of FEA capabilities for analysis and encourage additional learning in the subject
- Review the basic equilibrium equations for stress, strain, dynamics, etc., used in FEA
- Give students a basic understanding of how the equations are integrated across a complex geometric shape
- Introduce the concepts of meshing, element order and shape, shape functions, boundary conditions, number of elements, accuracy, and convergence of an FEA model
- Make students aware of the danger and potential misuse of FEA results.

The approach is to add FEM lecture material and FEA computer assignments to the existing Tool Engineering course. The lecture material will review the basic mechanical equilibrium equations and discuss ways that the equations can be applied to complex shapes. Lecture examples will also involve the concepts of element order and shape, number of elements, and the relation of these to accuracy of the analysis and the need to verify results. The computer assignments will give the students exposure to the techniques and capabilities of FEA software. The exercises will involve element and meshing alternatives, demonstrate model convergence issues, and illustrate the use and misuse of analysis results.

II. Curriculum Design

II.A Lecture Material

Several issues were taken into consideration in developing the lecture material for FEM and its use as an analysis tool for fixture and tooling design. Although students have had statics and strength of materials pre-requisite courses (and usually dynamics, a required 200-level support course for manufacturing engineers), they have seen few applications to manufacturing engineering and are typically out of practice with the computations. The need to refresh them with mechanics and dynamics details is balanced against the desire to give an overall perspective on FEM and the need to cover many other topics in the course. The approach developed is to examine in detail the mechanics and solution of the relatively simple one-dimensional problem and then explain more generally how two and three-dimensional elements are used in a similar but more computationally-intensive manner. Programming issues such as the speed of the analysis and the efficient use of matrices are avoided entirely in favor of a mechanical understanding of the principles at work. A set of numerical examples is given illustrating the one-dimensional statics problem including finite element issues such as boundary conditions, element size, shape functions, nodal matrices, constitutive models, and solution approximations. Discussion is then used to summarize the extension to 2-D and 3-D, the general approach to dynamic and thermal problems, and the practical questions and issues that FEA can be used to resolve. A determined approach is also made to stress the danger in blind interpretation of results, the need for verification experiments, and the opportunities available for further study and grounding in FEM fundamentals. Supplemental readings such as the Porsche case study[1] and the Robinson[5] and Kimball[6] articles are assigned to support the discussion.

A total of between three and six hours of lecture (1-2 weeks of a 10-week quarter) are developed on the subject of FEM. Lecture content generally follows the recommendations seen in other articles[7,11-13,16-17]. Discussions and numerical examples cover the following topics (more than one may be covered each hour): mechanics review of motion and deformation of single and multi-degree-of-freedom one-dimensional spring elements; formation of nodal matrices for solution of multi-degree-of-freedom one-dimensional spring elements; approximation of one-dimensional continuous structures; shape functions and the nature of the finite element approximation; generic specification of boundary conditions; two and three-dimensional modeling issues; and summary discussion of mesh density, element types, analysis types, and FEA limitations and abuses. Several qualitative and quantitative questions on the course exam are used to test learning of the subject.

II.B Computer Exercises

Some practical considerations guided the formation of computer exercises for giving students a hands-on experience with FEA. Since lab access to the software is limited, the exercises had to be completed during the students' three-hour lab periods or during short supervised evening activities. Furthermore, although it was desired to utilize only the basic functions of the software to get across the main ideas, the parts or tools analyzed should be realistic and serve as examples for potential advanced projects. It was assumed that all students had basic solid modeling experience since one of the pre-requisite courses covers modeling (using ProEngineer© software). Prior to the FEM portion of the Tool Engineering course the students gain further practice modeling assembled components (a machining fixture) with a solid modeler.

Two computer exercises using ProMechanica© software were developed for the class:

Exercise #1: Simple Part in Vise Jaws

The first exercise is a simulation of a simple beam-shaped part fixed in a set of vise jaws (see Figure 1). The students model the part and jaws as an assembly, assign material properties and appropriate constraints and loads to simulate an end milling process, and then use the FEA software to determine deflection (quality error) of the part. An existing end milling process model is used to relate cutting conditions to estimated forces. During class, the instructor gives a quick physical demonstration of the process and measures resulting quality. Figure 2 shows example analysis results for a static vertical load on the end of the beam. A written summary is to be turned in for the assignment, including student answers to several questions. The students are asked to compute the theoretical deflection based on simple beam mechanics. The students then compare the FEA results to the theory and the experiment to gain confidence with the method, much like the approach suggested by Hillsman[10]. Students are asked to re-run the analysis for a different material and a different beam thickness and comment on results. Students are asked to re-run the analysis using different load configurations (line and area load) and

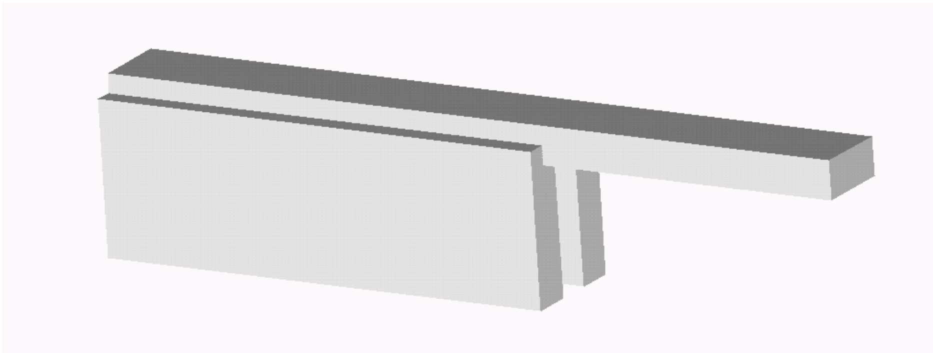

Figure 1 Part-Fixture Model for Computer Exercise #1

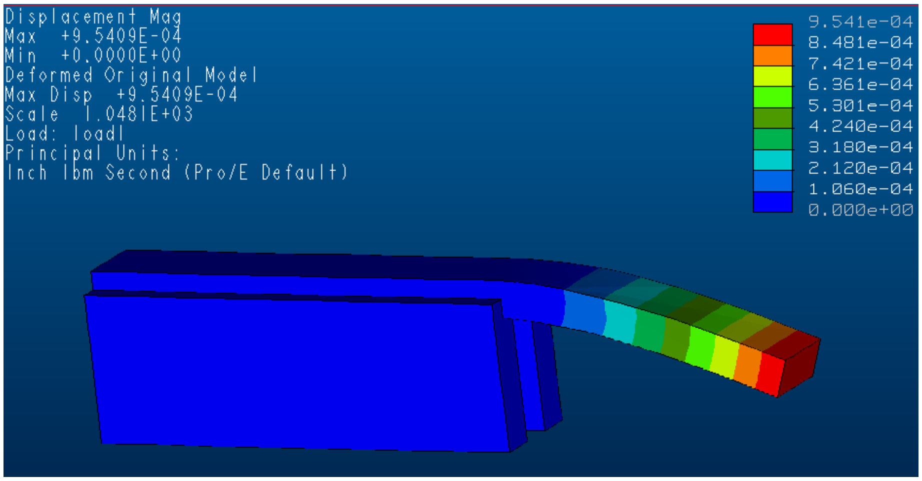

Figure 2 Static Deflection Analysis Results for Computer Exercise #1

element sizes and comment on results, including convergence time. Finally, students are asked to turn in several plots of the results so that they become familiar with the software capabilities.

Exercise #2: Complexity of Angle Plate

The second exercise demonstrates modeling of a more complex part and the effect of complex features on the analysis. The fixture to be modeled is an angle plate, shown in its simplest form in Figure 3. Students are asked to run an analysis on the plate to determine deflection of the top of the plate due to a static load in the same region and the natural frequency of vibration of the plate structure. Students are asked to note the number of solution steps and the convergence time for the solver. Next, the students add various complex model features to the plate and re-run the analysis to observe differences. The plate can have a series of holes in the vertical wall, rounds or chamfers on its edges, or extra material in the form of brackets, pins, or buttons placed on the wall. All of these are realistic features that help turn the plate into a working fixture. The students re-run the analysis, again noting the number of solution steps and convergence time. The students can try different meshing alternatives and element shapes to improve software performance. In their written conclusions, they must weigh the advantages of including the complex features in the analysis (better accuracy?) against the shorter convergence time of the simpler plate.

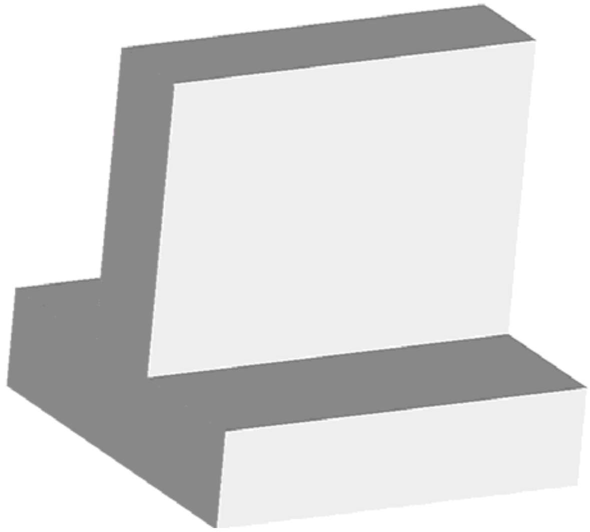

Figure 3 Simple Angle Plate Model for Computer Exercise #2

Other Exercises: Not Currently Appropriate for Class

Three other exercises were developed but were found to be impractical for immediate use in the course. More advanced software or faster computing speed may make them potential exercises for a future offering of the course. One of the exercises involves simple fixturing of a very complex part design. This problem is more typical of those attempted by mechanical engineers since it is the deformation of the complex part that is studied rather than the fixture. It is an important problem for tool designers as well, however, since supporting pins or other fixture elements may decrease deformation of the part during processing. Very long convergence times make this exercise impractical for current implementation. Another exercise involved a dedicated nest fixture that envelopes a part on all sides. The fixture itself is fairly complex and is to be modeled as an assembly with the part. The general complexity of the contact conditions, the loading conditions, and the motion constraints made this exercise impractical for course use at this time as well. Finally, one other exercise was attempted that involves modeling of a stamping die and blank for determining stress and fracture conditions in a sheet metal stamping operation. The goal of the exercise is to determine the optimal clearance distance between punch and die to result in fracture at a specified location in the part material. Unfortunately, a simple modeling approach could not be found that yielded reasonable convergence and clear results. Therefore, this exercise, too, was deemed beyond the current level of the Tool Engineering course.

III. Implementation

The new curriculum design with FEM lecture and exercise material was integrated into the Spring 2000 offering of Tool Engineering at Cal Poly. 10 students were enrolled in the class and all participated in the new material. Approximately 3 hours of lecture time were used to present the FEM material described above. Only one of the computer exercises was assigned (#1 above) because the others were not in a completed state at the time of the offering. About an hour of additional lecture time was used to explain and demonstrate the computer exercise. Different loading conditions were assigned to each student so that each would get a different answer for the displacement. The exercise was completed by the students outside of regular class and lab time. Unfortunately, no physical demonstration of the machining process could be completed during course time. Several questions on course exams tested the students knowledge and experience with both lecture and exercise material. Questions specifically covered the terms used for an FEM analysis. An additional numerical problem involved a one-dimensional spring deflection set-up, specified in terms of finite elements. Surveys distributed at the end of the course were used to gain student feedback and measure satisfaction with the new material. The FEM material will again be presented in the Spring quarter of 2001.

IV. Results and Discussion

Students mostly performed well on both the computer exercise and the exam questions covering lecture material. All but one student completed the computer exercise exactly as requested. They were each able to define motion constraints, apply process loads, set material properties, use the software mesh generator, run the static displacement analysis, plot results, and determine the deflection of the part in the vise for the given process forces. Nearly all students performed well on the FEM portion of the exam that covered knowledge of the terms used in FEM. Results were mixed, however, on the one-dimensional spring problem. Several students were not able to formulate the mathematical representation of the problem using element matrices to determine node displacement.

Student feedback on the use of FEM in the class was generally positive. All who commented liked the exposure to computer-aided engineering as it applied to tool design. The students appreciated gaining familiarity with an important problem-solving tool used in industry. Although the students seemed somewhat surprised to be performing static stress and deflection analysis in the class, they seemed to understand the need to master the basic concepts underlying the computer analysis. The students, however, stated that they wanted more time in class and during the quarter to learn the theoretical material. While the students had solved some of the same problems in pre-requisite classes, they needed more experience with formulating the problems as finite element representations. The three hours dedicated in class time was not enough to give them a firm grasp of the mathematical approach.

V. Summary and Conclusions

New material was developed for a junior-level Tool Engineering course designed for manufacturing engineering majors. The course covers design and analysis of fixtures and other tools for processing of materials. The new material introduces computer-aided analysis of parts and fixtures so that the students gain exposure to the latest industrial technology for tool design and they can seek further specialized training in the methods. The finite element method (FEM) is introduced as an analysis tool during lecture and specific software is utilized for computer exercises. The new material was implemented during the Spring quarter 2000, and the following conclusions were drawn:

- The lecture material designed to cover the basics of FEM theory was able to convey an introductory understanding of the terms and general solution procedures employed by the method.

- Three hours of lecture coverage was not enough to give students in the course an understanding of the material through enough for them to solve even a simple statics problem from beginning to end using a finite element formulation.
- The computer exercise was successful in giving students familiarity with commercial FEA software and exposing them to its potential uses.
- Students liked and appreciated the exposure to modern analysis techniques used for tool design and mechanical design.

In addition to the implementation described above, several other computer exercises were developed or created for introducing students to other FEM concepts such as meshing, element shapes, model complexity, dynamic analysis, and solution convergence issues. Although the importance of verifying results and interpreting software output with skepticism was stressed in class, no physical experiments were performed in the Spring 200 class to confirm results for the students.

Future use of FEM in the Tool Engineering class (the next offering at Cal Poly is scheduled for Spring 2001) should utilize both computer exercises described above as well as the machining demonstration for output verification. Between 4 and 6 hours of lecture and numerical homework assignments should be dedicated to FEM theory to ensure that students can formulate the mathematical solution for the most basic analysis cases. Further investigation of software capabilities should be made to examine the potential for utilizing some of the other computer exercises discussed.

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